EFFECT OF VARIABILITY AND CENTRAL TENDENCY IN PERFORMANCE-RELATED SPECIFICATIONS FOR CONCRETE PAVEMENTS

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ABSTRACT

Performance-related specifications (PRS) for the acceptance of newly constructed jointed plain concrete pavements (JPCP) have been developed over the past decade. A PRS is a construction specification that describes the target levels of key materials and construction acceptance quality characteristics (AQC's) that have been found to correlate with key pavement performance indicators (distresses and smoothness). These AQC's (e.g., initial smoothness, thickness, strength, air content, and percent consolidation around dowels) are amenable to acceptance testing at the time of construction.

PRS also provide rational methods for contract price adjustment based on the difference between the as-designed (target) and as-constructed life cycle costs (LCC's) of the pavements. PRS employ distress and smoothness prediction models to accurately relate the AQC's to future pavement performance and associated LCC.

This paper shows a complete sensitivity of the central tendency (mean) and variability (standard deviation) of key AQC's related to PRS developed for JPCP. The analysis is conducted using data from a recently completed PRS project in Indiana (I-465) and an ongoing PRS project in Florida (I-295). Specifically, this analysis demonstrates the influence of AQC quality on pay factor (an indicator of pavement performance). This information is particularly beneficial to contractors because it helps identify the key AQC's (and quality level for each) on which they should focus to ensure that 1) the provided quality satisfies the highway agency and 2) the incentive payment is maximized. This work shows the critical factors and variations of those factors that can lead to improved quality pavement and lower LCC.

Key words: life-cycle costs, jointed plain concrete pavement, pay adjustment, variability, acceptance quality characteristics, and performance.

INTRODUCTION

Performance-related specifications (PRS) are construction specifications that describe the target levels of key materials and construction acceptance quality characteristics (AQC's) that have been found to correlate with key pavement distresses and smoothness indicators (e.g., cracking and faulting, and International Roughness Index (IRI)). These AQC's (e.g., concrete strength, slab thickness, and initial smoothness) are amenable to acceptance testing at the time of construction.

PRS also provide rational methods for contract price adjustment based on the difference between the as-designed (target) and as-constructed life cycle costs (LCC's) of the pavements. PRS employ distress prediction models in an attempt to relate the AQC's to future pavement performance and associated LCC. The same distress models are used in both the as-designed and as-constructed present worth LCC computations. This process is illustrated in figure 1. This concept of PRS is adopted by the FHWA through the PaveSpec 3.0 software. (1, 2)

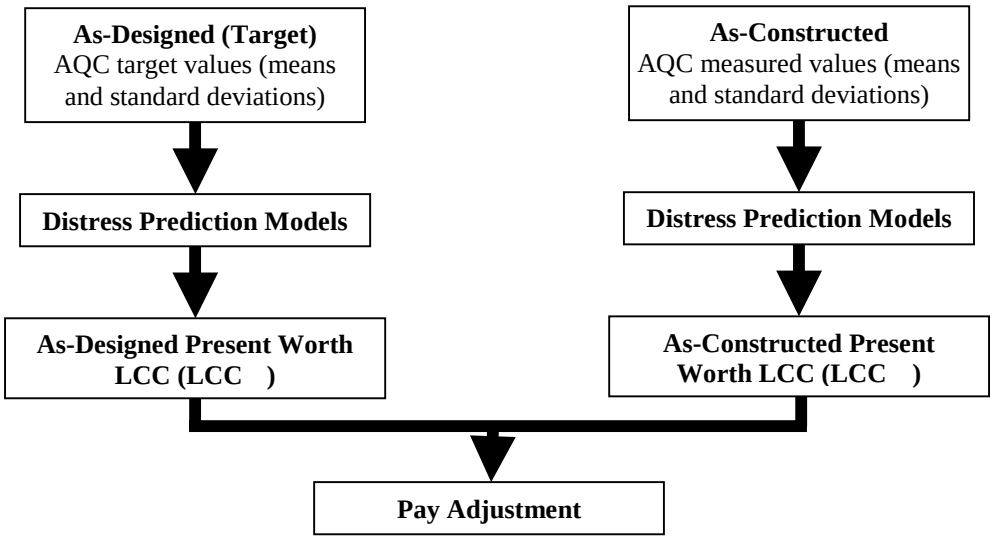

Figure 1. Basic concepts of LCC-based PRS.

PRS use Monte Carlo simulation for estimating the effect of construction and material variability on pavement performance. Currently, the effect of variability has not been sufficiently researched and is generally unknown (i.e., it has not be quantified). However, the Monte Carlo simulation technique yields a theoretical effect that appears to be realistic. Using Monte Carlo simulation, this and similar effects are handled automatically so that the user does not need to know much about statistics to get accurate results.

Monte Carlo simulation is widely used for studying real-world systems that contain elements of uncertainty that can be quantified in probabilistic terms. This simulation technique uses random numbers to sample from probability distributions and produce hundreds or thousands of scenarios (called iteration, trials, or runs). A complete Monte Carlo simulation thus uses results from each individual iteration. (3)

Mean and standard deviation values for the as-designed quality characteristic are entered into the PaveSpec 3.0 software to represent the variability in these quality characteristics. The as-designed (target) mean and standard deviation values are determined based on the design or agency policy and past experience. For each pavement lot, hundreds (or thousands) of Monte Carlo iterations are run. For each iteration, a value of each quality characteristic is selected from a normal distribution, defined by a given mean and standard deviation, and a LCC is computed. This process is illustrated in figure 2.

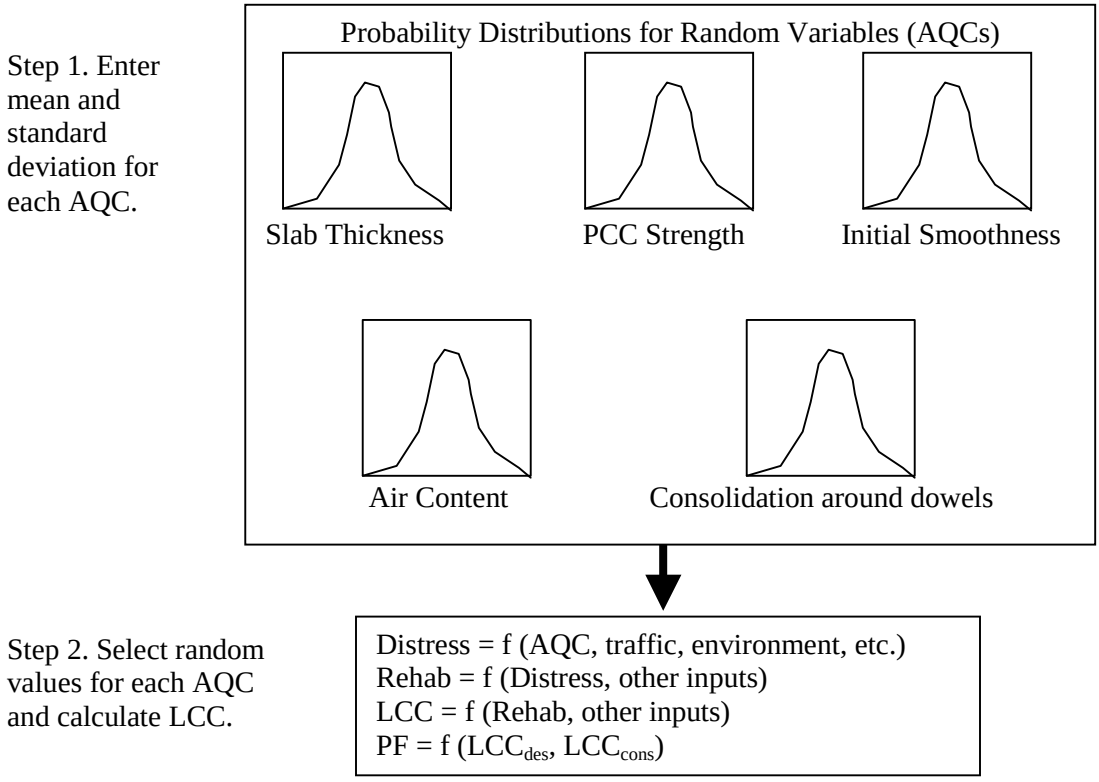

Figure 2. Illustration of the Monte Carlo simulation in PRS.

The objective of this paper is to evaluate the effect of AQC quality (mean and variability) on pavement performance using real-world projects. Two real-world JPCP projects in Indiana (I-465 in Indianapolis) and Florida (I-295, 9A in Jacksonville) are used in this sensitivity analysis. As was indicated in figure 1, pavement performance can be quantified in terms of the present worth of LCC or in terms of pay factor (a function of the difference between present worth of as-designed and as-constructed LCC's). For the analysis in this paper, pavement performance is expressed as a pay factor (percent of original bid price of PCC pavement). The equation for computing pay factor is shown below:

$$PF = 100(BID + [LCC_{des} - LCC_{con}]) / BID$$

Where:

PF = Pay factor, percentage of bid price
BID = Contractor's bid price, $
LCC_{des} = Present worth of as-designed life cycle cost, $
LCC_{cons} = Present worth of as-constructed life cycle cost, $

CONSTRUCTION PROJECTS

To compute LCC's, PRS require collecting pre-construction data about site conditions, design, maintenance and rehabilitation (M&R) policies and costs, etc. The following sections summarize the pre-construction data for the Indiana and Florida projects. These data were obtained from the design documents, construction plans, historical field test data, and inputs from the Indiana and Florida Departments of Transportation (INDOT and FDOT) personnel.

Design and Site Conditions

Both the Indiana and Florida projects are located in urban areas and carry heavy traffic loading. The Indiana project was constructed in the summer and fall of 2000 on I-465 in Indianapolis, whereas the Florida project will be constructed in the summer of 2002 on the 9A section of I-295 in Jacksonville. The Indiana project consists of 3 standard lanes [3.7-m (12-ft) wide] per direction and is approximately 1.5-mile long. The Florida project consists of 2 standard lanes [3.7-m (12-ft) wide] and a widened lane [4.3-m (14-ft)] per direction and is approximately 0.5-mile long. Table 1 summarizes key design features and site conditions for the Indiana and Florida projects.

Table 1. Site conditions and design features

Feature	**I-465**	**I-295 (9A)**
Type	JPCP	JPCP
Initial ESAL, million	2.03	1.0
Subgrade k-value, MPa/m (pci)	27 (100)	54 (200)
Climate	Wet-Freeze	Wet-No Freeze
Slab thickness, mm (in)	356 (14)	318 (12.5)
Dowel diameter, mm (in)	38 (1.5)	32 (1.25)
Joint Spacing, m (ft)	6 (19.7)	4.9 (16)
Base Type	Permeable Granular	Non-Permeable Granular
Outside Shoulder	Tied PCC	Tied PCC

Performance-Based M&R Policy

The LCC includes future maintenance and rehabilitation costs. The timing and type of future maintenance and rehabilitation activities are determined based on the predicted distresses and

IRI. Thus, different designs may have different future maintenance and rehabilitation activities, depending on the future distresses and IRI. In PRS, measurements of AQC's are obtained from each sublot and performance is also predicted on a sublot-by-sublot basis. A sublot is defined as a portion of a lot. The following M&R policies were defined by INDOT and FDOT and used in this analysis.

Indiana:

- Reseal 40 percent of transverse joints and 25 percent of longitudinal joints every 5 years, and 100 percent of cracks every 3 years [unit cost = \$3.3-3.9/m (\$1-1.2/ft)].
- Pre-overlay repairs: repair 100 percent of spalled joints using partial-depth repairs [unit cost = \$435/m^2 (\$364/yd^2)] and replace 100 percent of cracked slabs using partial-slab replacement [unit cost = \$161/m^2 (\$135/yd^2).
- Consider a sublot failed and apply an asphalt concrete (AC) overlay if percent slabs cracked exceed 10 percent, percent spalled joints exceed 10 percent, mean transverse joint faulting exceeds 0.25 in, or IRI exceeds 2.8 m/km (175 in/mi).
- Apply global rehabilitation that consists of AC overlay to the entire lot if 20 percent of the sublots are failed [unit cost of AC overlay = \$13.1 /m^2 (\$11/yd^2)]: first overlay = 7 years, second overlay = 7 years, third overlay = 5 years, fourth overlay = 3 years.

Florida:

- Reseal 50 percent of transverse joints, 50 percent of longitudinal joints, and 100 percent of cracks every 5 years [unit cost = \$3.3-3.9/m (\$1-1.2/ft].
- Pre-overlay repairs: repair 100 percent of spalled joints using partial-depth repairs [unit cost = \$435/m^2 (\$364/yd^2] and replace 100 percent of cracked slabs using full-slab replacement [unit cost = \$164.7/m^2 (\$137.8/yd^2)].
- Consider a sublot failed if percent slabs cracked exceed 15 percent, percent spalled joints exceed 30 percent, mean transverse joint faulting exceeds 2.5 mm (0.1 in), or IRI exceeds 2.4 m/km (150 in/mi) [unit cost = \$13.1/m^2 (\$11/yd^2)].
- Apply global rehabilitation to the entire lot if 25 percent of the sublots are failed: First global rehabilitation consists of full-depth slab replacement of cracked slabs, partial-depth joint repair of spalled joints, and diamond grinding [lasts for 10 years and costs \$3.6/m^2 (\$3.01/yd^2). Second and third global rehabilitations consist of AC overlay [lasts for 10 years and costs \$13.1/m^2 (\$11/yd^2)].

AQC Targets

Both INDOT and FDOT decided to base the PRS on concrete strength, slab thickness, and initial smoothness. Although PaveSpec 3.0 allows for considering air content and percent consolidation around dowels, both INDOT and FDOT decided not to include these AQC's in the PRS. AQC targets are agency-chosen means and standard deviations that define the agency's desired quality (the AQC quality for which the agency is welling to pay 100 percent of the bid price). Table 2 shows the target means and standard deviations for Indiana I-465 and Florida I-295 projects.

Table 2. Target Acceptance Quality Characteristics for Each Site

AQC	Parameter	I-465	I-295 (9A)
Concrete strength	Test	28-day flexural (beams)	28-day compressive (cylinders)
	Mean, MPa (psi)	4.8 (700)	31 (4500)
	Standard Deviation, MPa (psi)	0.34 (50)	4.2 (610)
Slab thickness	Test	cores	cores
	Mean, mm (in)	356 (14)	318 (12.5)
	Standard Deviation, mm (in)	13 (0.5)	13 (0.5)
Initial Smoothness	Test	Profile Index (0.2-in blanking band)	Profile Index (0.2-in blanking band)
	Mean, mm/km (in/mi)	110 (7.0)	47 (3.0)
	Standard Deviation, mm/km (in/mi)	47 (3.0)	16 (1.0)

AQC SENSITIVITY ANALYSIS

Using PaveSpec 3.0, a sensitivity analysis was conducted to evaluate the effect of the mean and variability of the AQC's considered in the PRS on pay factors. A pay factor (percentage of bid price) that is greater than 100 percent indicates that the pavement quality is superior to the targets and the contractor would receive a pay increase. A pay factor that is less than 100 percent indicates that the pavement quality is inferior to the targets and the contractor would receive a pay decrease.

Concrete Strength

The results of the sensitivity analysis for concrete 28-day flexural strength on Indiana I-465 project and for concrete 28-day compressive strength on Florida I-295 project are summarized in figures 3 and 4.

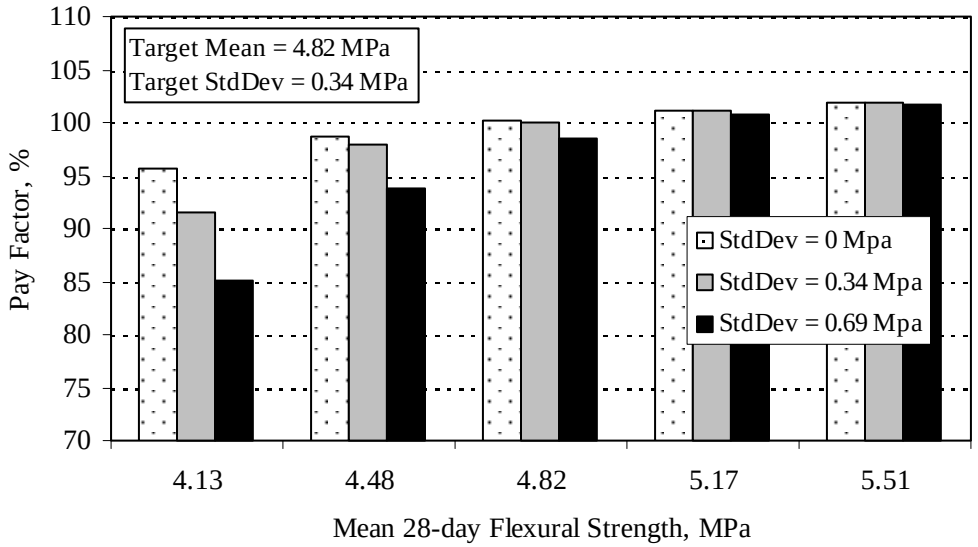

Figure 3. Effect of concrete strength mean and variability on pay factor (Indiana, I-465)

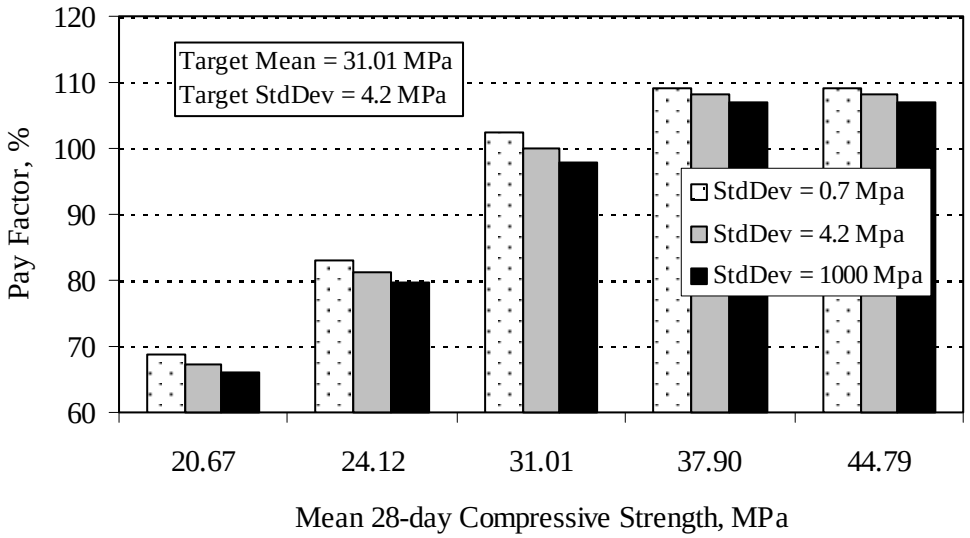

Figure 4. Effect of concrete strength mean and variability on pay factor (Florida, I-295)

An increase in mean strength results in an increase in the pay factor. When the strength is lower than the target the impact of variability of strength is very significant. The greater the variability the lower the pay factor. This is a logical result since lower strength concrete results in increased slab cracking and joint spalling that results in increased repair costs and earlier rehabilitation of the lot. When the strength is higher than the target, the impact of strength variability is almost insignificant. The obvious reason for this is that with a higher mean strength, the pavement is not likely to crack from fatigue loadings. Also, figure 4 shows that incremental changes in lower-than-target mean values have a greater effect on the pay factor than do the same increased changes in higher-than-target mean values. This supports the prevalent State DOT practice of assigning pay factors that decrease more drastically as the quality decreases.

Slab Thickness

The results of the sensitivity analysis for slab thickness on Indiana I-465 project are summarized in figure 5. An increase in mean slab thickness results in an increase in the pay factor. The impact of variability of thickness is not very significant either below or above the target. This result may be due to the large thickness of the pavement (i.e., high reliability).

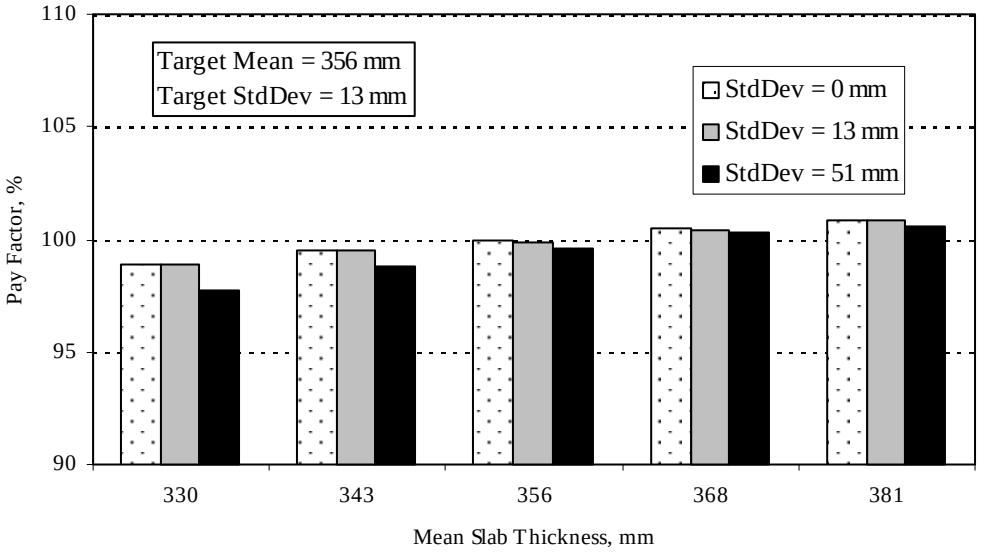

Figure 5. Effect of slab thickness mean and variability on pay factor (Indiana, I-465)

The results of the sensitivity analysis for thickness on Florida I-295 project are summarized in figure 6. An increase in mean thickness results in an increase in the pay factor. When the thickness is lower than the target, the impact of variability of thickness is very significant. The greater the variability of thickness the lower the pay factor. When the thickness is higher than the target, the impact of thickness variability is still significant in this case.

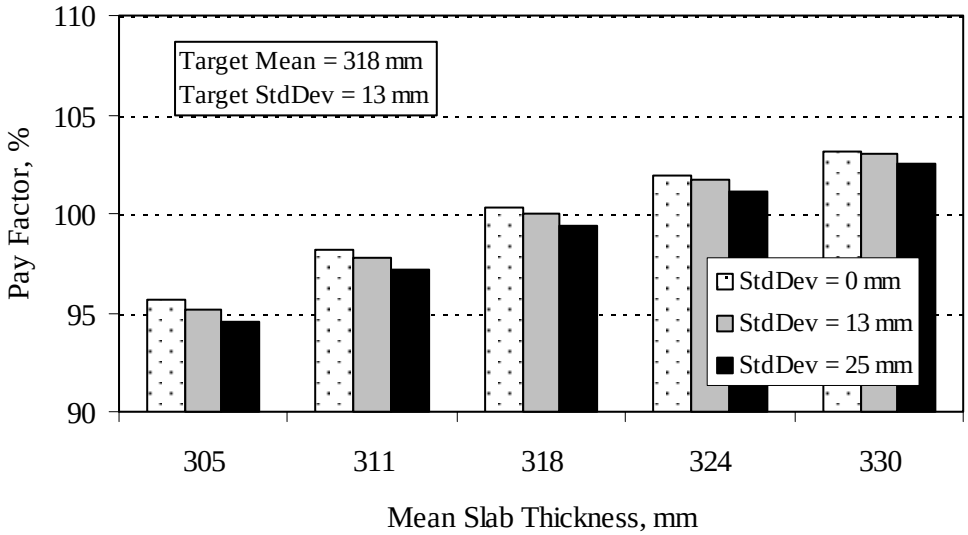

Figure 6. Effect of slab thickness mean and variability on pay factor (Florida, I-295)

Initial Smoothness

The results of the sensitivity analysis for initial smoothness (as measured by PI) on Indiana I-465 project and on the Florida I-295 project are summarized in figure 7 and 8. An increase in mean PI results in a significant decrease in the pay factor on average. When the PI is lower than the target, the impact of variability of PI is very significant. The greater the variability in PI (from sublot to sublot) the lower the pay factor. When the PI is higher than the target, the impact of PI variability is insignificant.

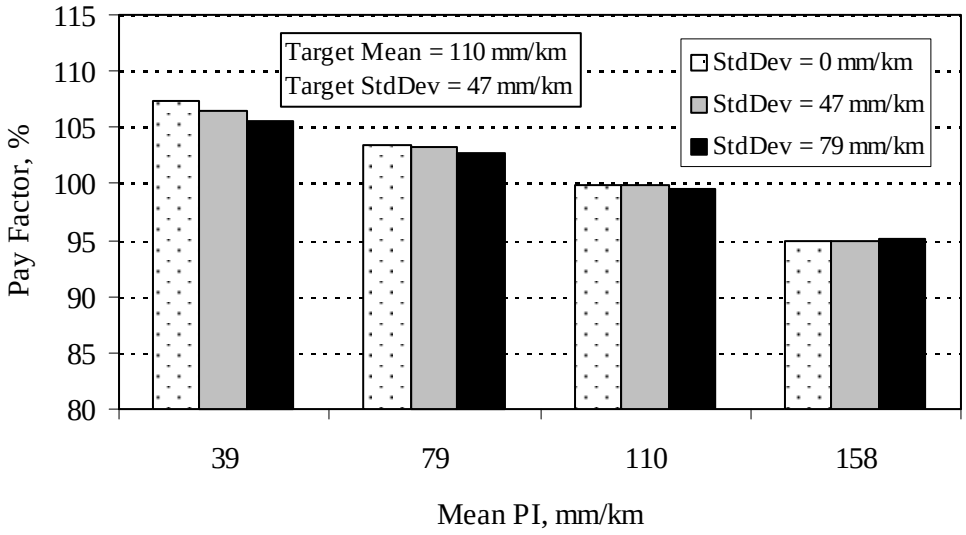

Figure 7. Effect of initial smoothness mean and variability on pay factor (Indiana, I-465)

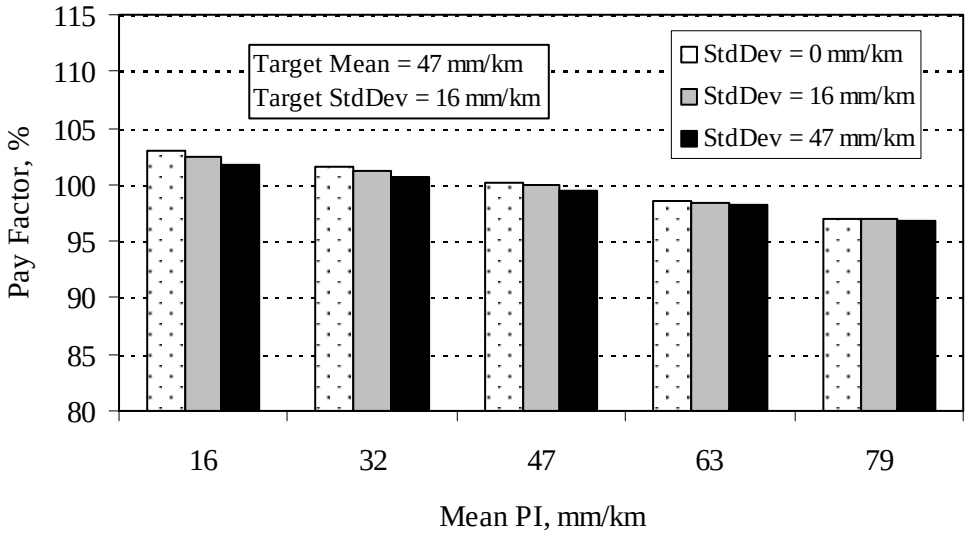

Figure 8. Effect of initial smoothness mean and variability on pay factor (Florida, I-295)

CONCLUSIONS

The sensitivity analyses were easy to conduct with PaveSpec 3.0 once the inputs were established. One run (1,500 simulated lots) produced all the necessary tables and charts to show the effect of mean and standard deviation of strength, thickness, smoothness on pay adjustment factors.

This study yields some important insight into the influence of materials and construction variability on performance. As the influence of variability on performance has not been well investigated any effort that can be done to better understand the relationship between variability and performance would be extremely helpful at this time.

The PaveSpec simulation approach shows that the pay factor always decreases or remains the same (for conservative designs) as the variability increases. Most engineers believe such relationship between variability and pay factor makes intuitive sense. However, this relationship is theoretical and has not yet been demonstrated from field data. At least one other theoretical relationship between variability and performance has been presented (the PAVAN model, which does not necessarily result in decreased performance with increased variability). (4)

Specific conclusions based on the sensitivity analysis that was conducted in this study using the Indiana I-465 and Florida I-295 PRS projects are shown below.

- Performance (i.e., either LCC or PF) is a function of both central tendency (i.e., the mean) and variability (i.e., the standard deviation). For conservative designs (high reliability), the effect of variability on performance (and, thus, pay adjustment) is very limited.

- For strength and thickness, the effect of variability on performance decreases as the central tendency improves (i.e., moves toward the target mean or better). In other words, variability has a greater effect on performance when the central tendency is unsatisfactory. For smoothness, the effect of variability on performance increases as the central tendency improves.

- Improving central tendency has a greater effect on performance than improving (i.e., decreasing) the variability. The following example is provided to illustrate this conclusion using flexural strength with design mean at 4.8 MPa (700 psi) and design standard deviation of 0.34 MPa (50 psi). A mean of 5.5 MPa (800 psi) (good) together with a standard deviation of 0.69 MPa (100 psi) (not good) performs better than a mean of 4.8 MPa (700 psi) (target) with a standard deviation of 0.34 MPa (50 psi) (target) and performs as well as a mean of 5.3 MPa (775 psi) (good) with a standard deviation of 0 (excellent).

- In most cases, decreasing the variability does not affect performance as much as increasing the variability. To illustrate, with a 4.8 MPa (700 psi) (target) mean, the pay factor increase resulting from decreasing the standard deviation from 0.34 MPa (50 psi) to 0 MPa (0 psi) is half the pay factor decrease resulting from increasing the standard deviation from 0.34 MPa (50 psi) to 0.69 MPa (100 psi). This can be seen as an argument against using incentives

solely to achieve uniformity, since the increased performance is minimal when the standard deviation is lower than the target standard deviation.

- Incremental changes in lower-than-target-quality mean values have a greater effect on performance than do the same incremental changes in better-than-target-quality mean values.

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